Monitoring of prefailure phase and detection of tool breakage in micro-drilling operations

Eiji Kondo, Kenji Shima

Abstract

The purpose of this study is to investigate effectiveness of the thrust force, the motor current of spindle, and the AE signals from workpiece for the monitoring of the prefailure phase and the detection of the tool breakage in drilling holes through a thin stainless steel plate (JIS SUS304). The thrust forces, the motor current, and the AE signals were measured in micro-drilling tests by using the micro-drills of 0.1 - 0.3 mm in diameter. After some considerations of experimental data, it was revealed that the thrust force is the most suitable for both the monitoring of the prefailure phase and the detection of the tool breakage, the motor current for the monitoring of the prefailure phase of the tool breakage, and the AE signal for the detection of the tool breakage.

Keywords: Monitoring; Micro-drilling; Prefailure phase; Tool breakage; Detection

1. Introduction

Micro holes machined by using micro-drills with a diameter of less than 1 mm have been widely required in parts production of various kinds of equipments. Monitoring of the prefailure phase and the detection of the tool breakage are required due to achieve high quality and productivity in micro-drilling operations since the micro-drills are more likely to fracture than the conventional drills. Consequently the detection of the micro-drill breakage has already been studied in previous papers [1][2]. In this method, both the thrust force and the micro-drill velocity are used for the identification of the prefailure phase with the wavelet based encoding and the neural networks because it is very difficult to observe the condition of the micro-drill to interpret the noisy sensory signals. Another improved method similar to the method mentioned above also needs the complex procedure to detect the tool breakage although it uses only the thrust force as a signal for the estimation [3]. They aimed to propose a universal method applied to various tool breakage types but almost tool breakage is expected to be caused by the excessive tool wear at the tool life under suitable drilling conditions [4]. In addition to it, the sensitive dynamometers are very expensive and limited to usage of drilling smaller parts. According to previous studies on conventional drillings [5] [6], the motor current of spindle could be a candidate of useful signal for the monitoring and the detection since it is easily measured with low cost [5]. The AE signal could also be a candidate of useful signal since it is well known that AE sensors have high sensitivity to rubbing and failure of materials at a low price [6]. The purpose of this study is to investigate effectiveness of the thrust force, the motor current of spindle, and the AE signals from workpiece for the monitoring of the prefailure phase and the detection of the tool breakage in drilling holes through a thin stainless steel plate (JIS SUS304). Wet micro-drilling tests, using a diameter of the micro-drill as experimental parameter, were carried out to measure the thrust forces, the motor current, and the AE signals when the
micro-dills were fractured by plugging drilled holes with chips.

2. Experimental Apparatus and Conditions

Micro-drilling tests were carried out on a vertical machining center with an additional high-speed spindle system. The experimental apparatus used in this study is shown in Fig.1 and the experimental conditions are shown in Table 1. The workpiece material was stainless steel JIS SUS304. Stainless steel plates of 0.5 mm in thickness were drilled with commercial micro-drills of 0.1 - 0.3 mm in diameter, as shown in Fig. 2. The workpiece was supported with the flame structure jig made from Bakelite shown in Fig. 1 in order to make outlet of drilled hole accessible. The micro-drill was not monotonously fed but was repeatedly fed up and down by step depths during one stroke, which is called peck drilling, with the oil mist. Micro-drilling tests, using a diameter of micro-drill as experimental parameter, were carried out. The thrust force in drilling through one hole was measured with a highly sensitive dynamometer. The motor current of spindle was measured from available current monitor terminal of the high-speed spindle system. The AE signals from workpiece were measured with an AE sensor attached on the workpiece plate.

Table 1. Experimental conditions

<table>
<thead>
<tr>
<th>Workpiece</th>
<th></th>
<th>JIS SUS304</th>
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<tbody>
<tr>
<td>Thickness</td>
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<table>
<thead>
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<th>Drill</th>
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<tbody>
<tr>
<td>Material</td>
<td></td>
<td>Cemented carbide</td>
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<tr>
<td>Diameter of shank</td>
<td></td>
<td>3 mm</td>
</tr>
<tr>
<td>Drill Diameter</td>
<td></td>
<td>0.1 mm 0.2 mm 0.3 mm 0.1 mm</td>
</tr>
<tr>
<td>Flute length</td>
<td></td>
<td>1.2 mm 2.4 mm 5.0 mm 1.2 mm</td>
</tr>
<tr>
<td>Coolant</td>
<td></td>
<td>Oil mist (micro emulsion) Dry</td>
</tr>
<tr>
<td>Step length</td>
<td></td>
<td>80 μm 60 μm</td>
</tr>
<tr>
<td>Spindle speed</td>
<td></td>
<td>10000 rpm</td>
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<tr>
<td>Feed rate</td>
<td></td>
<td>0.5 μm/rev</td>
</tr>
</tbody>
</table>

3. Tool Wear

Figure 3(a) shows the end of a worn micro-drill 0.1 mm in diameter (hereafter called 0.1 mm drill), as viewed in axial direction. The wear of flank face of main cutting edge shown in Fig. 3(a) is largest at the outer corner of the cutting edge, and it becomes smaller near the center of the drill. Figure 3(b) illustrates the end of the micro drill of 0.3 mm in diameter (hereafter called 0.3 mm drill), and the tool wear land is shaded. The shape of the wear land shown in Fig. 3(b) is different a little from the shape shown in Fig. 3(a); that is, the uniform width of flank wear land appears in middle of the main cutting edge in Fig. 3(b). Figure 4 shows the area of wear land of both the main cutting edges and the chisel edge. It can be seen from experimental results shown in Fig. 4 that the wear area $A_w$ rapidly increases in the early stage and then it gradually increases at almost constant wear rate as the number of the drilled holes $N$ increases.

(a) electron micrograph (φ 0.1 mm) (b) conceptual figure (φ 0.3 mm)

Fig. 3. Typical tool wear of micro-drill

Fig. 4. Area of wear land of both main cutting edges and chisel edge of micro-drill of 0.3 mm in diameter
4. Monitoring of Prefailure Phase of Tool Breakage

4.1. Thrust force of micro-drill

Figure 5 shows the thrust force $P$ in details over time as one hole was peck drilled with a slightly worn micro-drill through a thin stainless steel plate of 0.5 mm in thickness. First, the thrust force increases as the top corn of micro-drill penetrates into the workpiece, and then it keeps constant as the column body of micro-drill penetrates. Finally, the thrust force decreases when the top corn comes out from the workpiece surface. As a result, about six pulsed thrust forces have almost same amplitude, as shown in Fig. 5 since the step length was 80 $\mu$m and thickness of the stainless steel plate is 0.5 mm. Consequently average thrust force was defined as average value of the six pulsed thrust forces in this study.

Figure 6 shows the average thrust force $P_{av}$ and the horizontal axis represents the number of drilled holes. Obtained average thrust force $P_{av}$ rapidly increases in the early stage and then it gradually increases at almost constant rate as number of drilled holes increases. It can be seen that the average thrust force seem to be similar to the area of the tool wear land shown in Fig. 4.

According to previous study on conventional drilling, the thrust force caused by the tool wear increases as the area of the tool wear land increases [8]. Figure 7 shows that the incremental thrust force ($P_{av} - P_{av0}$) caused by the tool wear, where $P_{av0}$ is the average thrust force in drilling with a new micro-drill, monotonously increases as the area of the tool wear land $A_w$ increases.

4.2. Failure of micro-drills

The wear of the cutting edge of micro-drill gradually increased as the number of drilled holes increases, and the micro-drills fractured when the incremental thrust force caused by the tool wear exceeded a certain limit.

![Fig. 5. Detail of thrust force in peck drilling one hole with a slightly worn micro-drill 0.3 mm in diameter](image)

Fig. 5. Detail of thrust force in peck drilling one hole with a slightly worn micro-drill 0.3 mm in diameter

![Fig. 6. Average thrust force with increase of number of drilled holes](image)

Fig. 6. Average thrust force with increase of number of drilled holes

![Fig. 7. Increment of average thrust force with increase of area of tool wear land](image)

Fig. 7. Increment of average thrust force with increase of area of tool wear land

(a) φ 0.1 mm drill  (b) φ 0.3 mm drill

Fig. 8. Photographs of end of fractured micro-drills

Figure 8 shows the end of the fractured micro-drills. It can be considered from the shapes of the end of the fractured micro-drills shown in Fig. 8 that the micro-drills were fractured by normal stress since the fractured end face is approximately normal to the axis of the macro-drill [9]. Consequently it can be assumed that the breakage of the micro-drill was caused by the buckling shown in Fig. 9. Equation for the calculation of the buckling load $P_{max}$ based on the model shown in Fig. 9 can be expressed by Eq. (1).

$$P_{max} = \frac{2.046 \pi^2 EI}{\ell^2} \quad (1)$$

where $\ell$ is the flute length of the micro-drill, $E$ is the modulus of longitudinal elasticity of the drill material and $I$ is the second moment of the cross section of the
When it is assumed that the shape of the cross section of micro-drill is square with \( d \) in width and \( d/2 \) in height, the second moment \( I \) is expressed as \( d^4/64 \). Consequently buckling load \( P_{max} \) yields to Eq. (2).

\[
P_{max} = \frac{2.046 \pi^2 Ed^4}{64} \tag{2}
\]

Theoretical values calculated from Eq. (2) are expressed by the solid curve in Fig. 10 when \( E \) equals 480 GPa. In Fig. 10 the vertical axis is \( P_{max}l^2 \) which is defined as the maximum buckling load \( P_{max} \) multiplied by square the flute length \( l \). The modulus of longitudinal elasticity of the drill material \( E \) was identified by using the three point bending test. The theoretical values \( P_{max}l^2 \) increases exponentially as the drill diameter \( d \) increases since both axes of Fig. 10 are represented by logarithm. In Fig. 10 the experimental values \( P_{max}l^2 \) obtained by the buckling tests of micro-drills are expressed by the open square marks. The experimental values \( P_{max}l^2 \) obtained by the buckling tests almost coincide with the theoretical values expressed by the solid line. Consequently it is verified that Eq. (2) is suitable to calculate the buckling load of micro-drills. In Fig. 10 the experimental values \( P_{max}l^2 \) obtained by the drilling tests are also expressed by the open circle marks. It can be considered from the results shown in Fig. 10 that the micro-drills were fractured by the buckling load since the experimental values \( P_{max}l^2 \) obtained by the drilling tests almost coincide with the theoretical values.

### 4.3. Motor current of spindle

Figure 11 shows the motor current \( I \) in details over time. About six pulsed motor current shown in Fig. 11, except a few pulsed motor current at the beginning and the end, have almost same magnitude like the pulsed thrust force shown in Fig. 5. Figure 12 shows the average motor current \( I_{av} \) defined in the same manner as the average thrust force \( P_{av} \). Obtained average motor current \( I_{av} \) monotonously increases as number of drilled holes \( N \) increases, which is similar to the average thrust force \( P_{av} \) shown in Fig. 6. Consequently the average motor current \( I_{av} \) is expected to be closely related to the average thrust force \( P_{av} \). The average motor current \( I_{av} \) related with the average thrust force \( P_{av} \) is shown in Fig. 13 and it monotonously increases as the average thrust force \( P_{av} \) increases. However, in case of the 0.1 mm drill, the average motor current \( I_{av} \) is hardly related with the average thrust force \( P_{av} \) since the torque generated in drilling with the smaller micro-drill of 0.1 mm in diameter is too weak to generate enough motor current signal for monitoring of the tool breakage. In Fig. 13 the average motor current at the moment of the tool breakage, which are indicated by the symbol \( (P_{av})_{br} \), are the maximum, respectively, except the 0.1 mm drill.
4.4. AE signal from workpiece

Figure 14 shows the envelope of AE signal $E$ in details over time. It can be seen in Fig. 14 that the AE signal envelope does not react to the drilling workpiece. Figure 15 shows average of the AE signal envelope $E_{av}$. Obtained the average of the AE signal envelope $E_{av}$ seems to increase as number of drilled holes $N$ increases but it does not monotonously increases, which is different from the average thrust force $P_{av}$ shown in Fig. 6. Relationship between the average of the AE signal envelope $E_{av}$ and the average thrust force $P_{av}$ is shown in Fig. 16. It can be seen from Fig. 16 that the average of the AE signal envelope $E_{av}$ seem to be hardly related with the average thrust force $P_{av}$ and it is difficult to monitor of the prefailure phase of the tool breakage by it.

5. Detection of tool breakage

5.1. Tool breakage caused by large tool wear at tool life

Figure 17 shows the thrust force $P$, the motor current $I$, and the AE signal envelope $E$ in details over time when the 0.3 mm drill fractured at the tool life. It can be seen from 17(a) that the pulsed thrust force $P$ suddenly come to zero halfway in the step of tool feed. In other words, the width of the pulsed thrust force at the moment of the tool breakage was narrower than the width of the pulsed force in the normal micro-drilling. The motor current $I$ shown in Fig. 17(b) seem to be similar to the thrust force $P$ shown in Fig. 17(a). On the other hand, the AE signal envelope shown in Fig. 17(c) suddenly increases at the moment of the tool breakage although it kept almost constant until the tool fractured.

5.2. Breakage caused by unexpected exceed thrust force

Figure 18 shows the thrust force $P$, the motor current $I$, and the AE signal envelope $E$ in dry micro-drilling in details over time when the 0.1 mm drill suddenly fractured by exceed thrust force caused by plugging drilled hole with chips. The thrust force $P$ shown in 18(a) rapidly increases halfway in the step of the tool feed and then it comes to zero. The motor current $I$ shown in Fig. 18(b) does not change at the moment of tool breakage. The AE signal envelope shown in Fig. 18(c) suddenly and clearly increases at the moment of the tool breakage.

6. Conclusions

After some considerations of experimental data, results were reached as follows.

(1) Breakage of the micro-drill caused by the large tool wear at tool life could be predicted by the average thrust force which coincided with the theoretical
buckling load based on the simple model of the micro-drill body when the diameter of micro-drill was more than 0.1 mm. 

(2) Breakage of the micro-drill could be also predicted by the average motor current of spindle when the diameter of micro-drill was more than 0.2 mm.

(3) Breakage of the micro-drill could be detected by the instantaneous thrust force or the instantaneous AE signal envelope when the diameter of micro-drill was more than 0.1 mm.

(4) Breakage of the micro-drill could be detected by the instantaneous motor current when the diameter of micro-drill was more than 0.3 mm.

References


